# *CP* VIOLATION IN PSEUDO-DIRAC FERMION OSCILLATIONS

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**Ipek, McKeen, Nelson,** ***PRD*** **90 076005 (2014),** ***arXiv:*** **1407.8193**

# Sneak peek

- We need to have more *CP* violation for baryogenesis
- $U(1)_R$ symmetric SUSY brings new *CP* violation without EDM constraints
    - This model also has (pseudo-)Dirac fermions
    - Pseudo-Dirac fermions have oscillations between Dirac partners
    - There can be *CP* violation in these oscillations
    - This *CP* violation can give rise to a same sign dilepton asymmetry

# *CP* Violation in the Standard Model

**Only source:** Quark mixing matrix (CKM matrix)

$$-\frac{g}{\sqrt{2}}\left(\bar{u}\ \bar{c}\ \bar{t}\right)\gamma^{\mu}W_{\mu}^{+}\underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{\mathrm{CKM}}}\begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$V_{\mathrm{CKM}}$: 3 mixing angles + 1 irreducible phase

→ *CP* violation in the electroweak sector

# We need (more) *CP* violation

**Our Universe has a lot more matter than antimatter!**

**How?**

*baryogenesis:* Produce $10^8$+1 quarks for every $10^8$ antiquarks

- Baryon number violation ✔
- *CP* violation ✘
- Out-of-equilibrium conditions ✘

CKM phase gives an asymmetry of ~$10^{-20}$

suppressed by small mixing angles and Yukawa couplings

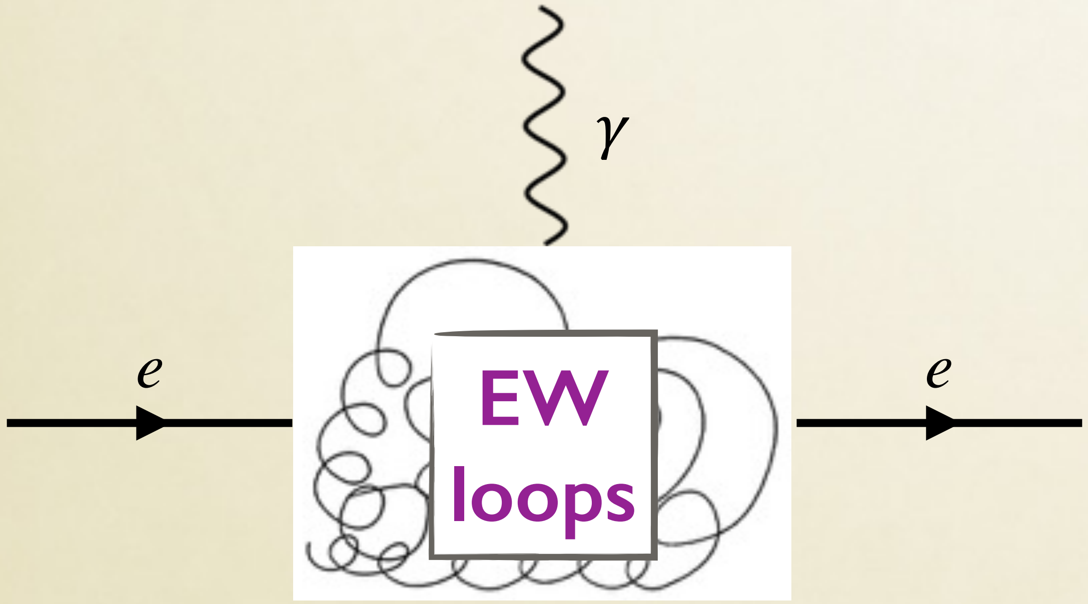
**We need more *CP* violation!**

# EDM Constraints on *CP* Violation

Electron electric dipole moment: $d_e \leq 0.87 \times 10^{-28}\ e{\cdot}\mathrm{cm}$

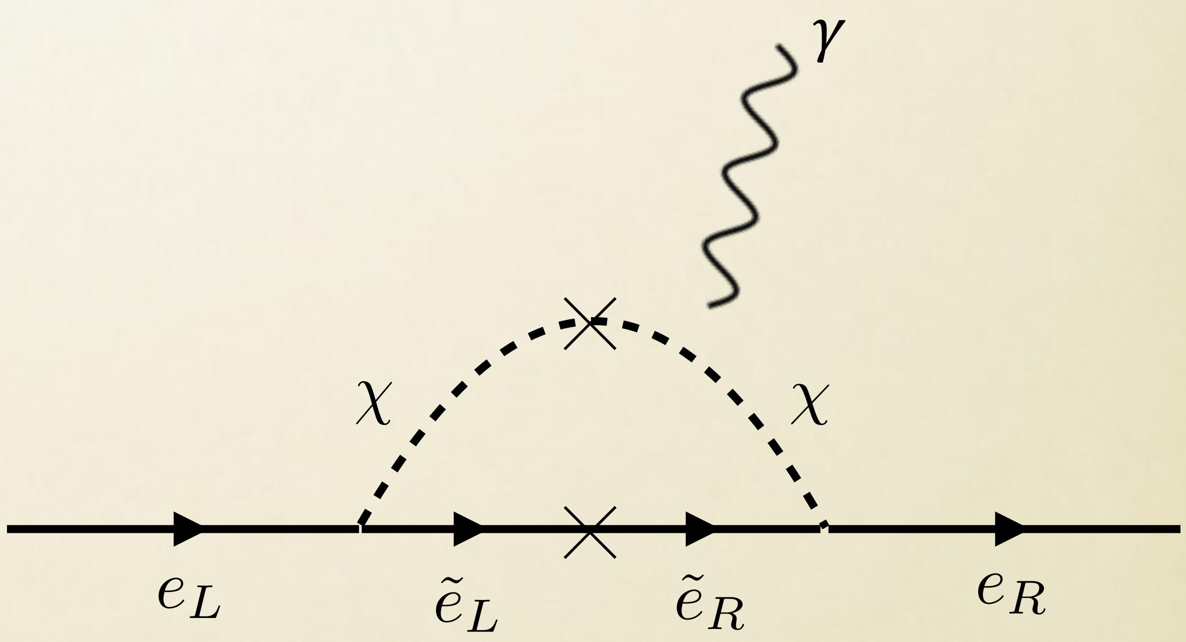
ACME, *Science* 343 (2014)

What we have in the SM:




$d_e \leq 10^{-38}\ e{\cdot}\mathrm{cm}$

What SUSY has:




**SUSY *CP* problem**

# Solution: $U(1)_R$ symmetric SUSY

Part of the field content:

| Field | $SU(3)$ | $SU(2)$ | $U(1)$ | $U(1)_R$ |
|---|---|---|---|---|
| $q_i$ | $3$ | $2$ | $1/6$ | $0$ |
| $\bar{u}_i$ | $\bar{3}$ | $1$ | $-2/3$ | $0$ |
| $\bar{d}_i$ | $\bar{3}$ | $1$ | $1/3$ | $0$ |
| $\ell_i$ | $1$ | $2$ | $-1/2$ | $0$ |
| $\bar{e}_i$ | $1$ | $1$ | $1$ | $0$ |
| $\phi_{\bar{d}_i}$ | $\bar{3}$ | $1$ | $1/3$ | $+1$ |
| $\lambda$ | $8$ | $1$ | $0$ | $+1$ |

SM fermions are not charged under $U(1)_R$

Sfermions and gauginos have +1 $U(1)_R$ charge


**Hall, Randall, *Nuc.Phys.B*-352.2 1991**
**Kribs, Poppitz, Weiner, *PRD* 78 2007**

# Electron EDM in $U(1)_R$ symmetric SUSY

Due to the $U(1)_R$ symmetry

- No Majorana masses for gauginos
- No left-right sfermion mixing

| Field | $SU(3)$ | $SU(2)$ | $U(1)$ | $U(1)_R$ |
|---|---|---|---|---|
| $q_i$ | $3$ | $2$ | $1/6$ | $0$ |
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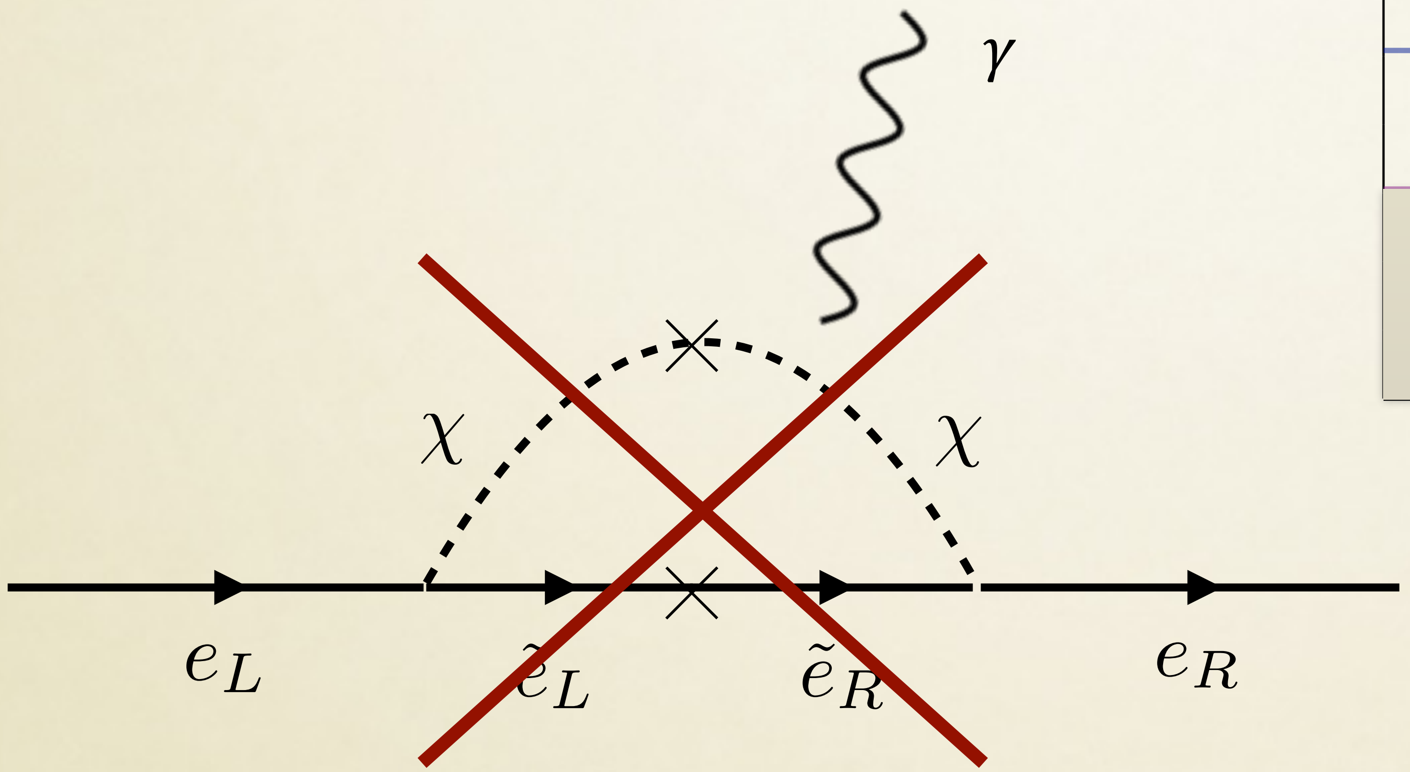


We can have large *CP* violating parameters without constraint

Hall, Randall, *Nuc.Phys.B*-352.2 1991
Kribs, Poppitz, Weiner, *PRD* 78 2007

# Need more fields

Make Dirac gauginos:

| Field | $SU(3)$ | $SU(2)$ | $U(1)$ | $U(1)_R$ |
|---|---|---|---|---|
| $q_i$ | $3$ | $2$ | $1/6$ | $0$ |
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| $\phi_{\bar{d}_i}$ | $\bar{3}$ | $1$ | $1/3$ | $+1$ |
| $\lambda$ | $8$ | $1$ | $0$ | $+1$ |
| $\mathcal{O}$ | $8$ | $1$ | $0$ | $-1$ |

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Sfermions and gauginos have +1 $U(1)_R$ charge

Dirac partner of gluino a.k.a. octino

Hall, Randall, *Nuc.Phys.B*-352.2 1991
Kribs, Poppitz, Weiner, *PRD* 78 2007

# Dirac fermions in $U(1)_R$ symmetric SUSY

- Dirac masses for gauginos ➞ new chiral adjoints

e.g. $\lambda \equiv (8,1,0)_{+1}$ gluino

$\mathcal{O} \equiv (8,1,0)_{-1}$ Dirac partner of gluino ≡ octino

- $\lambda$ and $\mathcal{O}$ are two (Weyl) components of a Dirac gluino

$$\psi = \begin{pmatrix} \lambda \\ i\sigma_2 \mathcal{O}^* \end{pmatrix}$$

with conserved $U(1)_R$ charge and a Dirac mass

$$-\mathcal{L}_{\rm mass} = m_D \lambda \mathcal{O} + m_D^* \lambda^\dagger \mathcal{O}^\dagger$$

# Pseudo-Dirac fermions

- $U(1)_R$ symmetry is always broken by supergravity!
- Approximate $U(1)_R$ ➞ Majorana masses for the gluino partners:

$$-\delta\mathcal{L}_{\text{mass}} = \frac{1}{2}\left(m_\lambda \lambda\lambda + m_\mathcal{O}\mathcal{O}\mathcal{O}\right) + \text{h.c.}$$

$$\psi = \begin{pmatrix} \lambda \\ i\sigma_2 \mathcal{O}^* \end{pmatrix}$$ ➞ **Pseudo-Dirac fermion**

$$\mathcal{H}_{\text{mass}} = \begin{pmatrix} m_D & m_M \\ m_M^* & m_D \end{pmatrix} \qquad m_M = \frac{1}{2}(m_\lambda^* + m_\mathcal{O})$$

with mass eigenvalues: $M_{1,2} = m_D \pm |m_M|$

corresponding eigenstates: $\frac{1}{\sqrt{2}}\left(|\psi\rangle \pm e^{-i\phi}|\bar{\psi}\rangle\right) \qquad \phi = arg(m_M)$

# Pseudo-Dirac fermion oscillations

- Mass eigenstates ≠ interaction eigenstates
  $\Longrightarrow$ oscillations

- A pseudo-Dirac fermion has 4 states:
  $(R^+,\uparrow)$, $(R^+,\downarrow)$, $(R^-,\uparrow)$, $(R^-,\downarrow)$

- Oscillations mix only 2×2 blocks:
  - $(R^+,\uparrow)$ can oscillate into $(R^-,\uparrow)$
  - $(R^+,\downarrow)$ can oscillate into $(R^-,\downarrow)$

work with 2-component Weyl spinors

Dreiner, Haber, Martin, *arXiv*:0812.1594

- Examples: neutrinos, mesinos, neutralinos

Wolfenstein, *Nucl Phys* B 186 (1981), …
Thomas, Sarid, *PRL* 85 (2000)
Grossman, Shakya, Tsai, *PRD* 88 (2013)

# Interactions: toy model

Consider the $U(1)_{\mathrm{R}}$-violating interactions:

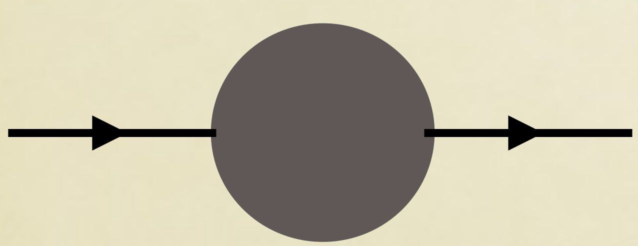
$$\mathcal{L}_{\text{int}} = -\phi^* \left(y_\lambda \lambda^a + y_{\mathcal{O}} \mathcal{O}^a\right) t^a \bar{d} + \text{h.c.}$$

$\phi$ = complex scalar (squark), $d$ = fermion (quark), $t^a$ = $SU(3)$ generator

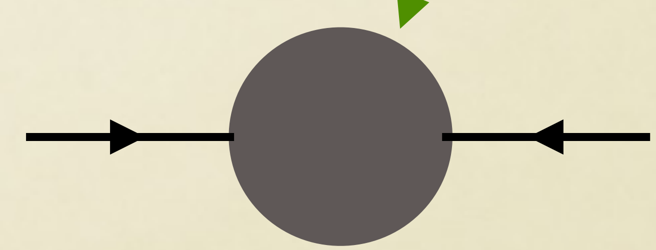
$\Rightarrow$ $M_{1,2}$ are modified

Solve: $\det\left[s\mathbb{1} - \left(1 - \Xi^T\right)^{-1} (m + \Omega) \left(1 - \Xi\right)^{-1} \left(\overline{m} + \overline{\Omega}\right)\right] = 0$

$$m = \begin{pmatrix} m_\lambda & m_D \\ m_D & m_{\mathcal{O}} \end{pmatrix}$$



$\propto \Xi$



$\propto \Omega$

$\propto m_d \Rightarrow 0$

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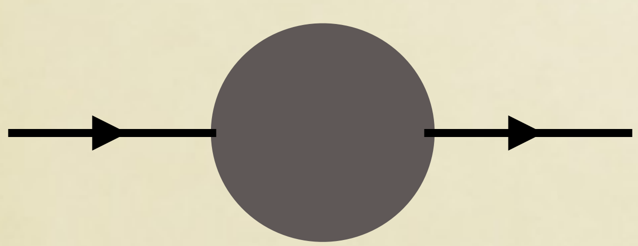
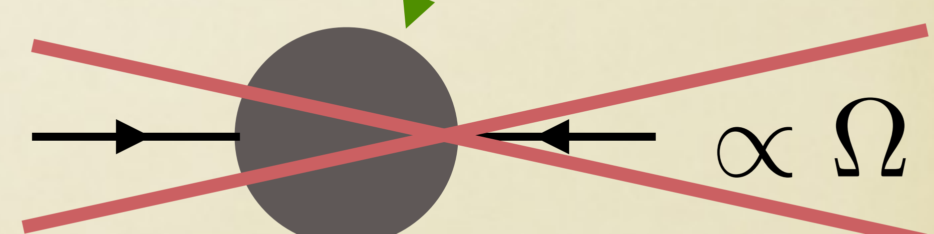


$\propto \Xi$



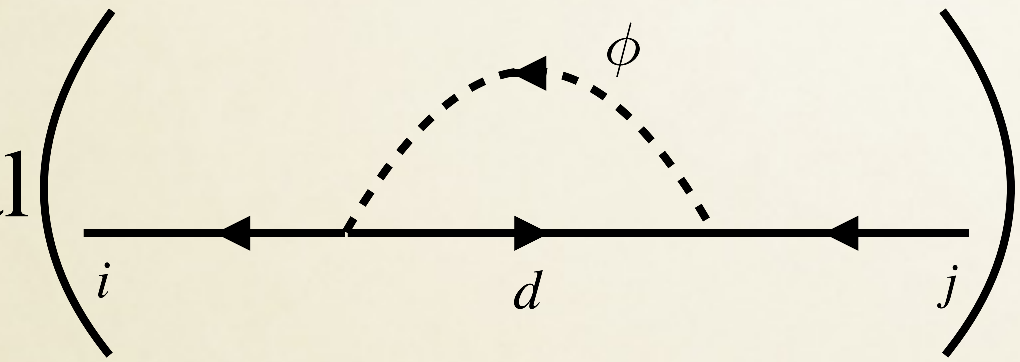
$\cancel{\propto \Omega}$

$\propto m_d \Rightarrow 0$

# Interaction Hamiltonian

$\mathcal{H}_{\text{mass}}$ + interactions $\Rightarrow$ effective Hamiltonian

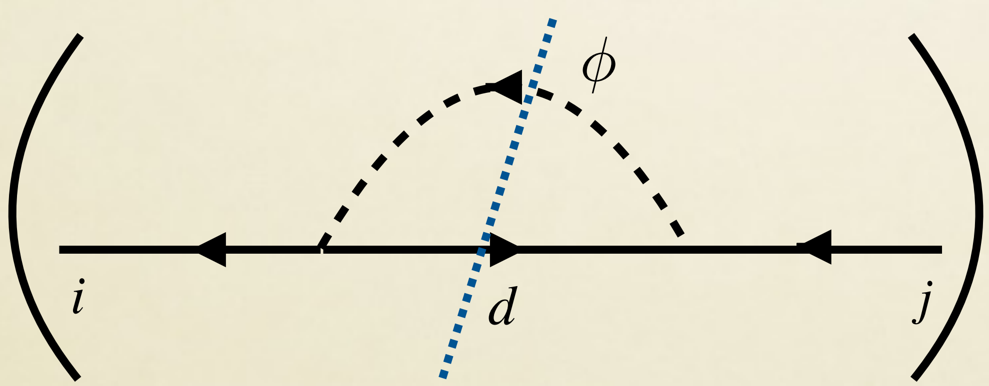
$$H = M + \frac{i}{2}\Gamma$$

- Real 

corrections to masses

$$M = \begin{pmatrix} M_D & M_M \\ M_M^* & M_D \end{pmatrix}$$

$i, j = \lambda, \mathcal{O}$

- Imaginary 

Width

$$\Gamma \simeq \frac{M_D}{64\pi}\left(1 - \frac{m_\phi^2}{M_D^2}\right)^2 \begin{pmatrix} |y_\lambda|^2 + |y_\mathcal{O}|^2 & 2y_\lambda y_\mathcal{O}^* \\ 2y_\lambda^* y_\mathcal{O} & |y_\lambda|^2 + |y_\mathcal{O}|^2 \end{pmatrix}$$

# Back to *real* life

Part of the field content:

2-component Weyl spinors

| Field | $SU(3)$ | $SU(2)$ | $U(1)$ | $U(1)_R$ |
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| $\phi_{\bar{d}_i}$ | $\bar{3}$ | $1$ | $1/3$ | $+1$ |
| $\lambda$ | $8$ | $1$ | $0$ | $+1$ |
| $\mathcal{O}$ | $8$ | $1$ | $0$ | $-1$ |
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Sfermions and gauginos have +1 $U(1)_R$ charge

Dirac partner of gluino

Extra superpartners

- λ is the lightest *R*-charged particle
- $\Phi_{D,\bar{D}} \rightarrow$ non-gauge couplings for $\Phi_{\mathcal{O}}$

**Ipek, McKeen, Nelson, *arXiv:* 1407.8193**

# Why gluinos?

- Gluinos are produced strongly
- "*[strong] interactions cause the state to decohere into a single mass eigenstate, thereby destroying the oscillation feature*" **Grossman, Shakya, Tsai, *PRD* 88 (2013)**

$$\frac{\partial \rho}{\partial t} = -i\,[H, \rho] - \underline{\frac{\kappa}{2}\,[N, [N, \rho]]}$$

**Tulin, Yu, Zurek, *JCAP* 1205 (2012)**

$\rho$ = density matrix, $\kappa$ = strength of interactions

$$\rho = \sum_{i,j=\psi,\bar{\psi}} |i\rangle\langle j|$$

modification due to:

$$\psi q \to \psi q$$
$$\bar{\psi} q \to \bar{\psi} q$$

$$N = \mathrm{diag}(1, -1) \quad \text{if} \quad \mathcal{L}_{int} \to -\mathcal{L}_{int} \quad \text{as} \quad \psi \to \bar{\psi}$$

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$$\rho = \sum_{i,j=\psi,\bar\psi} |i\rangle\langle j|$$

modification due to:

$$\psi q \to \psi q$$
$$\bar\psi q \to \bar\psi q$$

$$N = \mathrm{diag}(1,+1) \quad \text{if} \quad \mathcal{L}_{int} \to +\mathcal{L}_{int} \quad \text{as} \quad \psi \to \bar\psi$$

$\psi$ is an octet $\longrightarrow$ real $\longrightarrow$ strong interactions do NOT decohere $\psi$ and $\bar\psi$

# Dirac and Majorana masses

- Dirac gluino mass comes from:

$$\int d^2\theta \frac{c\, W'_\alpha}{\Lambda_M} W^\alpha \Phi_{\mathcal{O}} \quad \longrightarrow \quad m_D = \frac{cD}{\Lambda_M}$$

$W'_\alpha$ = spurion with a $D$-term, $W^\alpha$ = QCD superfield,

$\Lambda_M$ = messenger scale, $\Phi_{\mathcal{O}}$ = superfield with $\mathcal{O}$

- Majorana mass for gluino (from anomaly mediation):

$$m_\lambda = \frac{\beta_s}{g_s} m_{3/2}$$

**Randall, Sundrum, *Nucl.Phys.B* 352, 1991**
**Giudice, Luty, Murayama, Rattazzi, *JHEP* 9812, 1998**

$m_{3/2}$ = gravitino mass, $g_s$ = QCD coupling constant, $\beta_s$ = beta function for $g_s$

- Majorana mass for $\mathcal{O}$:

$$\int d^2\theta\, m_{\mathcal{O}} \Phi^2_{\mathcal{O}}$$

assume: $m_{\mathcal{O}} \ll m_D$

# 4-fermion interactions: gluino

Warning: Messy!

$U(1)_R$ violating: $y_{ijk}\ell_i q_j \phi_{\bar{d}_k}$

gauge: $\sqrt{2} g_s \bar{d}_i \lambda^a t^a \phi^*_{\bar{d}_i}$

$\boxed{G_{ijk}\lambda \ell_i q_j \bar{d}_k}$ 1

$$G_{ijk} = \frac{\sqrt{2} g_s y_{ijk}}{m^2_{\phi_{\bar{d}}}}$$

$U(1)_R$ violating: $y''_{ij}\bar{e}^*_i \bar{u}^*_j \phi^*_D$

mass mixing: $B^2_{D\bar{D}}\phi_D\phi_{\bar{D}},\ B^2_{D\bar{d}_i}\phi_D\phi_{\bar{d}_i},\ \tilde{m}^2_k \phi_{\bar{d}_k}\phi^*_{\bar{D}}$

scalar mass: $\mu_D \Phi_{\bar{D}}\Phi_D$

$\boxed{G'''_{ijk}\lambda \bar{e}^*_i \bar{u}^*_j \bar{d}_k}$ 2

$$G'''_{ijk} = \frac{\sqrt{2} g_s y''_{ij}(\tilde{m}^2_k B^2_{D\bar{D}} + \mu^2_D B^2_{D\bar{d}_k})}{m^2_{\phi_{\bar{d}}}\mu^4_D}$$

# 4-fermion interactions: octino

More of the same:

$$G''_{ijk} = \frac{g'_k y''_{ij}}{\mu_D^2}$$

$U(1)_R$ violating: $y''_{ij}\bar{e}_i^*\bar{u}_j^*\phi_D^*$

$U(1)_R$ conserving: $g'_i\bar{d}_i\mathcal{O}^a t^a\phi_D$

$U(1)_R$ violating: $y'_{ij}\ell_i q_j\phi_{\bar{D}}$

mass mixing: $B^2_{D\bar{D}}\phi_D\phi_{\bar{D}}$

$$\boxed{G''_{ijk}\mathcal{O}\bar{e}_i^*\bar{u}_j^*\bar{d}_k} \quad 3$$

$$\boxed{G'_{ijk}\mathcal{O}\ell_i q_j\bar{d}_k} \quad 4$$

$$G'_{ijk} = \frac{g'_k y'_{ij} B^2_{D\bar{D}}}{\mu_D^4}$$

# Interaction Lagrangian

$\boxed{G'''_{ijk}\lambda\bar{e}^*_i\bar{u}^*_j\bar{d}_k}$ 2 $\boxed{G''_{ijk}\mathcal{O}\bar{e}^*_i\bar{u}^*_j\bar{d}_k}$ 3

gives corrections to the Majorana mass! $\longrightarrow$ keep small

- CP violation is maximized when final states are indistinguishable

Focus on two terms:

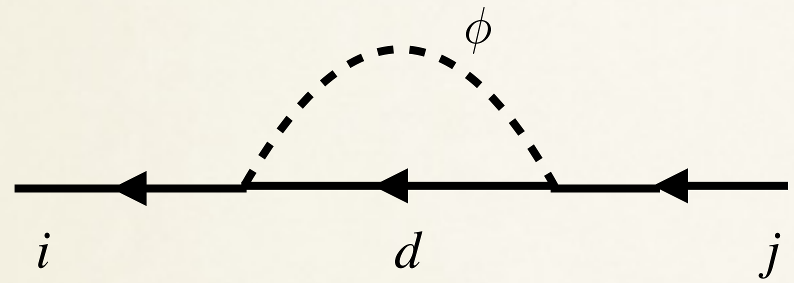
$\boxed{G_{ijk}\lambda\ell_i q_j\bar{d}_k}$ 1 $\boxed{G'_{ijk}\mathcal{O}\ell_i q_j\bar{d}_k}$ 4

$$\mathcal{L}_{\text{eff}} = \tilde{G}_\lambda \lambda \bar{d} q_1 \ell_2 + \tilde{G}_\mathcal{O} \mathcal{O} \bar{d} q_1 \ell_2$$

$G_{211} \equiv \tilde{G}_\lambda,\ G'_{211} \equiv \tilde{G}_\mathcal{O}$

# Pseudo-Dirac gluino self-energy

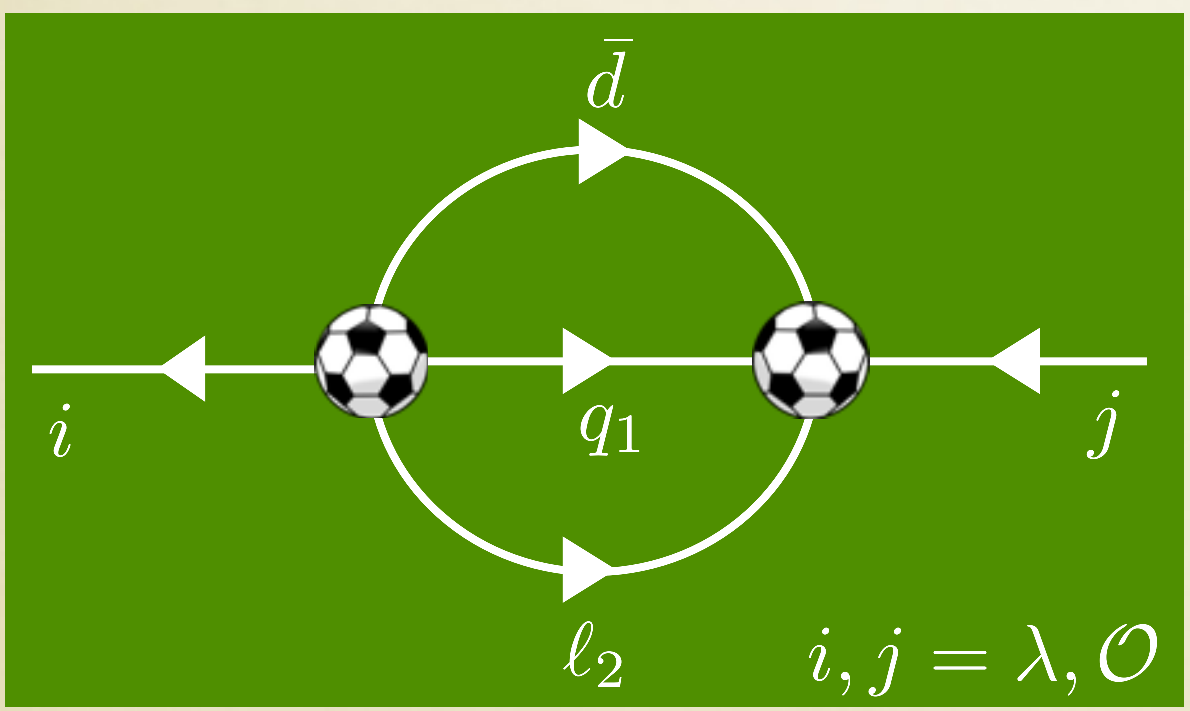
Toy model:




$$\Rightarrow \quad H = M + \frac{i}{2}\Gamma$$

- Squarks are heavier than the gluino → 1-loop self-energy is real
- Absorptive part at 2-loop order

$$\mathcal{L}_{\rm eff} = \tilde{G}_\lambda \lambda \bar{d} q_1 \ell_2 + \tilde{G}_\mathcal{O} \mathcal{O} \bar{d} q_1 \ell_2$$




$$\Im \left( \frac{\Xi_{ij}}{\tilde{G}_i \tilde{G}_j^*} \right) = \frac{2p^4}{3\,(16\pi)^3}$$

**soccer field diagram, David McKeen**

# Interaction Hamiltonian

Tree level masses + the soccer diagram = interaction Hamiltonian

$$H = M + \frac{i}{2}\Gamma$$

$$M = \begin{pmatrix} M_D & M_M \\ M_M^* & M_D \end{pmatrix}$$

corrections to the Majorana mass:

$$\delta_M \sim \frac{g_s g_k'}{(4\pi)^2}\left(\frac{\tilde{m}_k^2 B_{D\bar{D}}^2 + \mu_D^2 B_{D\bar{d}_k}^2}{\mu_D^4}\right) M_D$$

$$\Gamma \simeq \begin{pmatrix} \Gamma_0 & 0 \\ 0 & \Gamma_0 \end{pmatrix} + \frac{M_D^5}{12\,(8\pi)^3}\begin{pmatrix} |\tilde{G}_\lambda|^2 + |\tilde{G}_\mathcal{O}|^2 & 2\tilde{G}_\lambda^* \tilde{G}_\mathcal{O} \\ 2\tilde{G}_\lambda \tilde{G}_\mathcal{O}^* & |\tilde{G}_\lambda|^2 + |\tilde{G}_\mathcal{O}|^2 \end{pmatrix}$$

$\Gamma_0$ = non $\mathcal{L}_{\text{eff}}$ decays
e.g. gluon and gravitino

absorptive part of the soccer diagram

# Oscillations

$$H = M + \frac{i}{2}\Gamma$$ ➡ similar to neutral meson mixing Hamiltonian

- Eigenvectors: $$|\psi_H\rangle = p|\psi\rangle - q|\bar{\psi}\rangle$$ $$|\psi_L\rangle = p|\psi\rangle + q|\bar{\psi}\rangle$$ , with eigenvalues: $\omega_{H,L}$

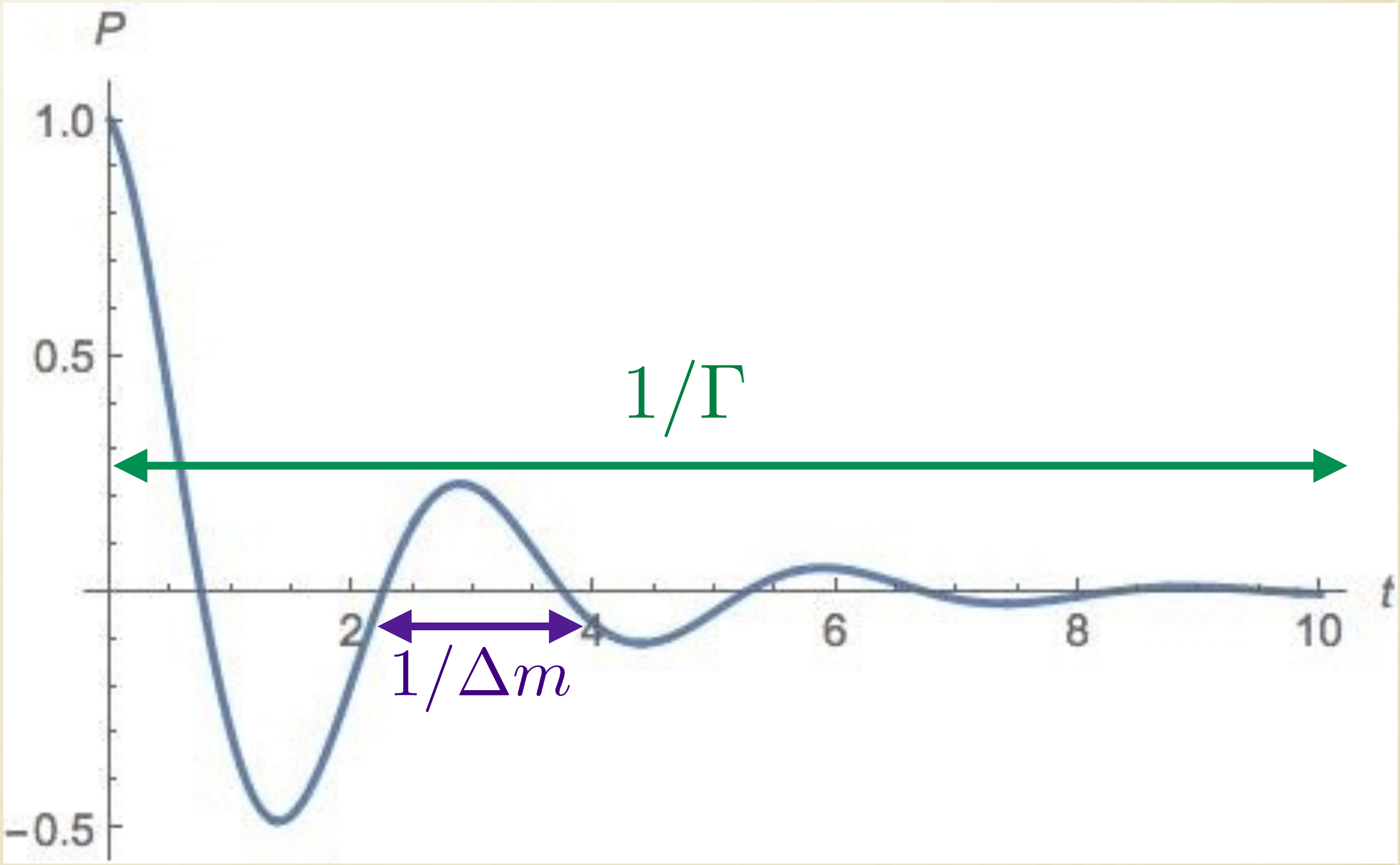
$H$ = heavy, $L$ = light

- Important: mass difference and the width

$$\Delta m = m_H - m_L = \Re(\omega_H - \omega_L)$$

$$x \equiv \frac{\Delta m}{\Gamma}$$

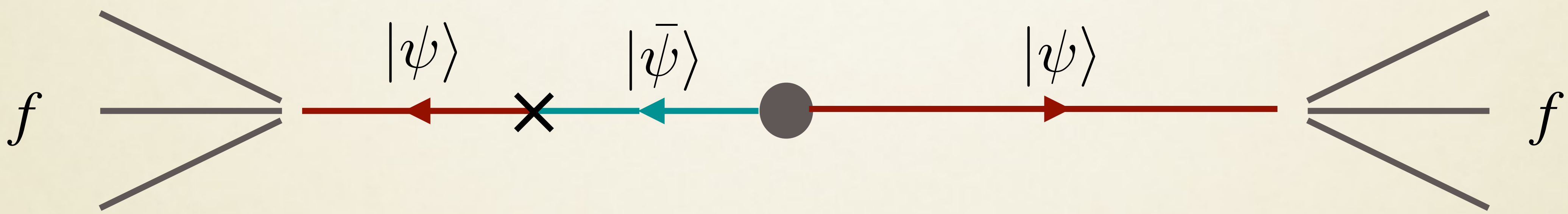
- $x \ll 1$: decay before oscillation
- $x \gg 1$: rapid oscillations
- $x \sim 1$: observe nice oscillations before decay



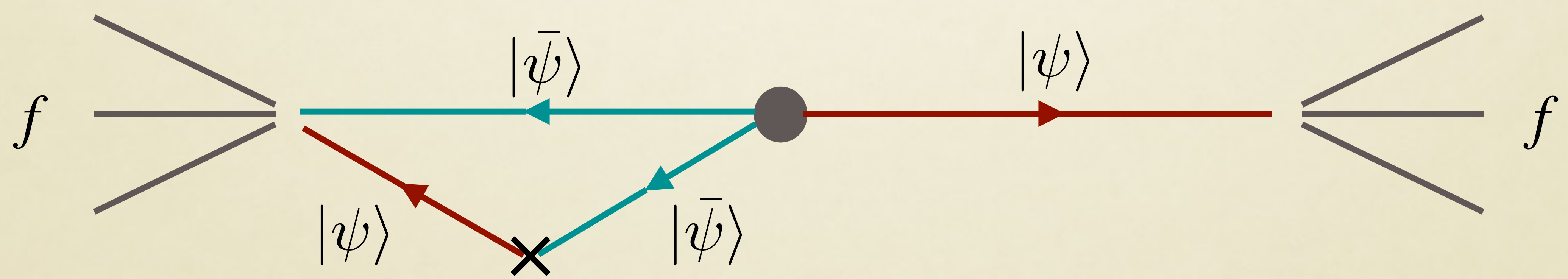
# *CP* Violation in Oscillations

- *CP* violation needs a relative phase between $M$ and $\Gamma$

- Two ways to get *CP* violation:
  1. In mixing: $|q/p| \neq 1$




  2. In interference between decays with mixing and without mixing:

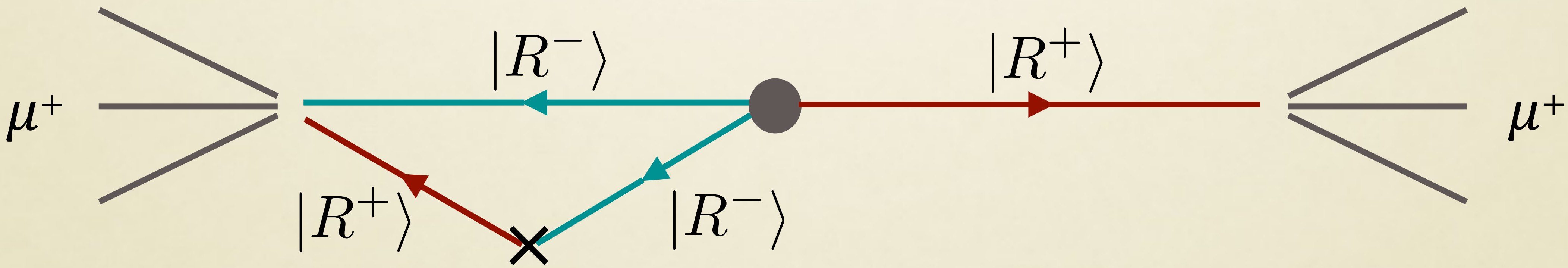


# $CP$ violation in gluino oscillations

$$\mathcal{L}_{\text{eff}} = \tilde{G}_\lambda \lambda \bar{d} q_1 \ell_2 + \tilde{G}_\mathcal{O} \mathcal{O} \bar{d} q_1 \ell_2 + \text{h.c.}$$

both states can decay into the same final state

can have $CP$ violation in interference between decays with mixing and without mixing




$|R^\pm\rangle$ = state with ±1 $U(1)_R$ charge

# Same-sign dimuon asymmetry

- *CP* violation can be observed as a same-sign dimuon asymmetry:

$$A \equiv \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$$

$N^{++}$ = number of events with two positively charged muons

A<1: more muons than antimuons $\longrightarrow$ CP violation!

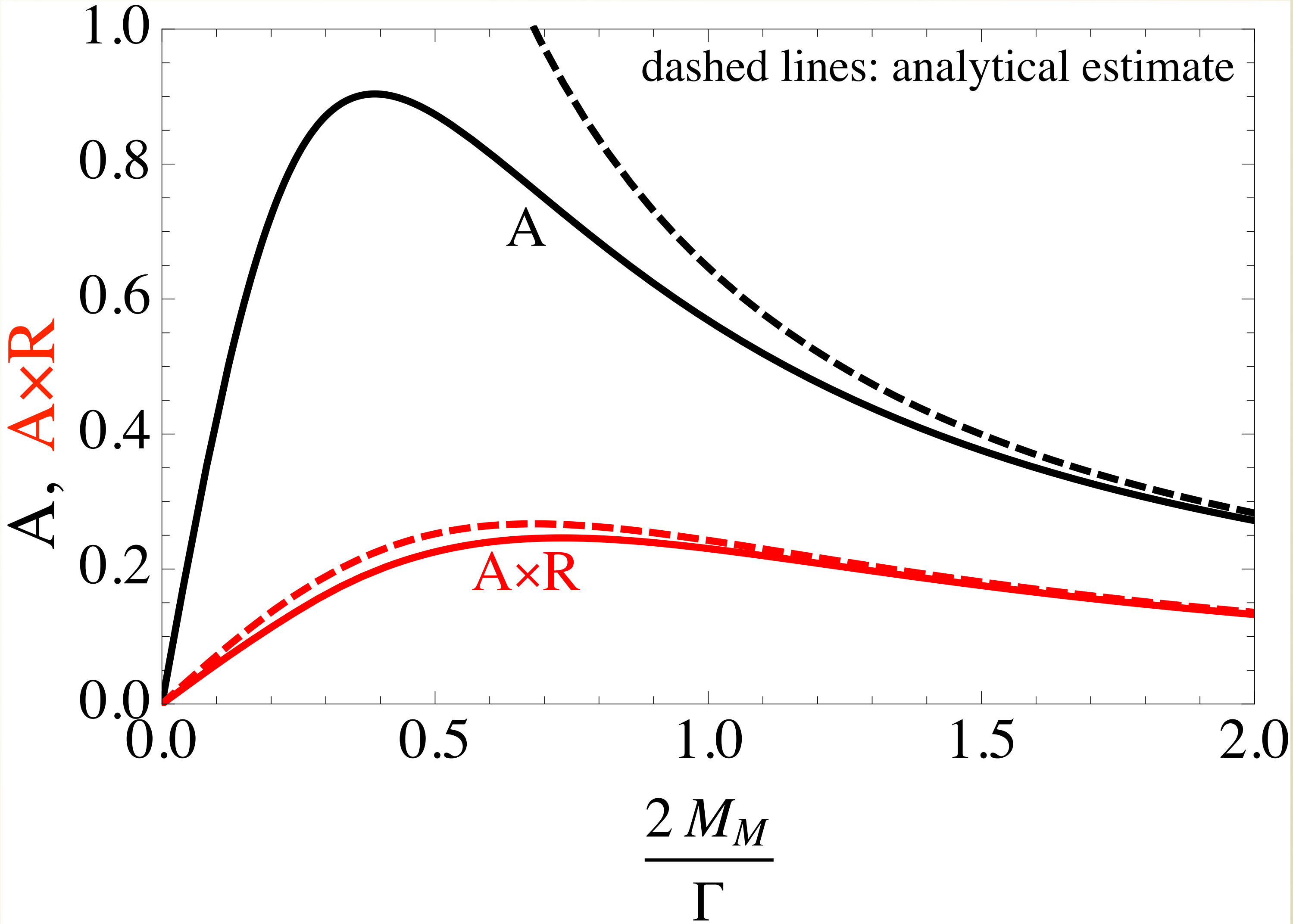
- Also important: fraction of same sign muon decays:

$$R \equiv \frac{N^{++} + N^{--}}{N^{+-} + N^{-+} + N^{++} + N^{--}}$$

$A \times R \propto$ how much asymmetry one can expect

# Let’s talk numbers

- gluino mass = 1.6 TeV
- scalar mass ($\mu_D$) = 5 TeV
- squark mass ($m_{\phi d}$) = 4 TeV
- gluino width ($\Gamma$) = 300 eV
- gravitino mass = 5 keV
- gravitino decays ($\Gamma_0$) small
- $\phi_\Gamma \equiv \arg \Gamma_{12} = -\pi/3$
- $\Delta m \simeq 2M_M$




**100 fb$^{-1}$, @13 TeV:** gluino production cross-section = 16 fb

400 same sign dimuon events for R = 0.25

Can probe *O*(10-20%) asymmetry

# Summary

- Pseudo-Dirac fermions are a feature of $U(1)_R$ symmetric SUSY
- They have particle—antiparticle oscillations
- There can be *CP* violation in the decays of oscillating pseudo-Dirac fermions
- This *CP* violation can be observed as a same-sign dimuon asymmetry at the LHC
- New sources of *CP* violation are always welcome! (baryogenesis)
- Similar *CP* violating effects can be present in other systems, e.g. mesino oscillations